41st IAHS WORLD CONGRESS
Sustainability and Innovation for the Future
13-16th September 2016
Albufeira, Algarve, Portugal

MOEEBIUS ENERGY PERFORMANCE OPTIMIZATION FRAMEWORK IN BUILDINGS FOR URBAN SUSTAINABILITY

Ander Romero[1]*, Borja Tellado[2], Tasos Tsitsanis[3]

1: Sustainable Construction Division
Tecnalia Research & Innovation
Parque Científico y Tecnológico de Bizkaia- C/Geldo, Edificio 700. E-48160 Derio (Spain)
e-mail: ander.romero@tecnalia.com, web: http://www.tecnalia.com

2: Energy and Environment Division
Tecnalia Research & Innovation
Parque Científico y Tecnológico de Bizkaia- C/Geldo, Edificio 700. E-48160 Derio (Spain)
e-mail: borja.tellado@tecnalia.com, web: http://www.tecnalia.com

3: Energy Labs
Hypertech S.A.
32, Perikleous str. GR-15232 Athens (Greece)
e-mail: t.tsitsanis@hypertech.gr, web: http://www.hypertech.gr – http://www.ht-energylabs.com

Keywords: Building-District Energy Simulation, Building Performance Optimization, Human-Centric Automation, Energy Services Market

Abstract *With the increasing demand for more energy efficient buildings, the construction and energy services industries are faced with the challenge to ensure that the energy performance and savings predicted during energy efficiency measures definition is actually achieved during operation. There is, however, significant evidence to suggest that buildings underperform illustrating a, so called, "performance gap" which is attributed to a variety of causal factors related to both predicted and in-use performance, implying that predictions tend to be unrealistically low whilst actual energy performance is usually unnecessarily high. In turn the successful penetration and effective application of ESCO business models relies on minimizing the gap between actual and predicted building energy performance. The aforementioned gap, though, prohibit the scaled deployment of energy efficiency projects constituting a significant barrier to the development of the ESCO market. The overall problem (performance gap) could be basically interpreted as an inability of current modelling techniques to represent the realistic use and operation of buildings. MOEEBIUS H2020 project introduces a Holistic Energy Performance Optimization Framework that enhances current (passive and active building elements) modelling approaches with advanced user behaviour modelling and machine learning technologies to create an innovative suite of end-user tools and applications enabling: (i) accurate Building Energy Performance prediction, (ii) precise allocation of detailed performance contributions between critical building components and operations, (iii) real-time building performance optimization, (iv) optimized retrofitting decision-making and, (v) real-time peak-load management optimization at the district level. Through the provision of a robust technological framework MOEEBIUS will enable the creation of attractive business opportunities for ESCOs, Aggregators, Maintenance and Facility Managers in evolving and highly competitive energy services markets.*

NOMENCLATURE

AUI: Ambient User Interface
BEMS: Building Energy Management System
BEPS: Building Energy Performance Simulation
BIM: Building Information Models
DAE: Dynamic Assessment Engine
DFMPC: Distributed Fuzzy Model Predictive Control
DHMS: District Heating Management Systems
DSS: Decision Support System
ESCO: Energy Service Company
EPC: Energy Performance Contract
HVAC: Heating, Ventilation and Air Conditioning
LCA: Life Cycle Assessment
LCC: Life Cycle Cost
M&V: Measurement and Verification
OPM: Occupant Profiling Mechanism
RES: Renewable Energy Source
ROI: Return-On-Investment
WSAN: Wireless Sensor and Actuator Network

1. INTRODUCTION

Post-Occupancy Evaluation studies in built and occupied buildings have demonstrated huge gaps between predicted and actual energy consumption. The measured energy use can be as much as 2.5 times the predicted energy use (more than 70% in retail, 100% in the residential, 150% in the offices sector, and over 250% in the education sector, using all high or all low values for what experts believe reasonably represents occupant behaviour) [1, 2, 3]. The magnitude and diversity of identified performance gaps highlights the need for deeper understanding of critical underlying performance factors related to the behaviour of occupants as well as other major building active elements.

The overall problem (performance gap) could be basically interpreted as an inability of current modelling techniques to represent realistic use and operation of buildings. Even the most detailed modelling and simulation programs still contain many simplifying assumptions, which can lead to significant energy deviations between prediction and real consumption [4]. In fact, current simulation tools do not accurately incorporate the impact of occupants' behaviour on the energy performance of buildings. This is usually attributed to the use of inadequate assumptions made about occupancy behaviour, which is highly varied and unpredictable. This inevitably leads to significant uncertainties in energy predictions [5].

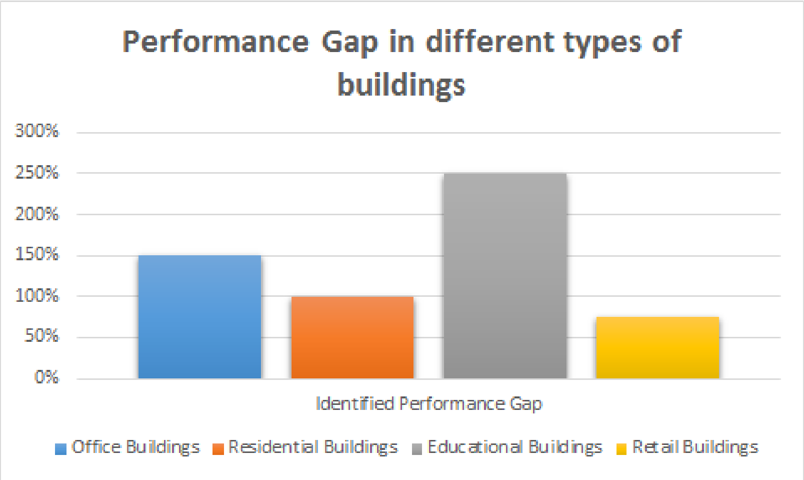

Figure 1. Performance Gap in different types of Buildings.

In addition to discrepancies caused by assumptions, other discrepancies that contribute to the growth of the gap between predicted and actual energy performance include: (1) the inability of existing static/ passive Building Information Models (BIM) to represent complexities of the actual building (thermal bridges, infiltrations, etc.), which leads to model simplifications, (2) alterations that take place over the building fabric, services, usage and controls during building life in comparison with original specifications (mismatch between design and construction - late design changes), (3) Non-efficient control strategies that do not allow for the full exploitation of the energy efficiency potential of a building and the optimization of its performance (control strategies that ignore the human factor), (4) loss of performance due to low quality building practices or ageing (poor workmanship, poor commissioning) and (5) environmental inaccuracies in the description of local weather, soil and adjacent structures/ vegetation.

Performance gap between predicted and measured energy performance of buildings has a direct negative impact on novel models of building management such as those based in Performance Contracts, as the EPC (Energy Performance Contracts) [6]. In more detail, the performance gap generates a consequent gap between payback estimates and techno-commercial Return-On-Investment (ROI) calculations in ESCOs (Energy Service Companies) projects. In turn ESCOs are forced to add installation and commissioning services, project management, man effort, measurement and verification (M&V) costs to hedge the risks induced by prediction uncertainty and inaccuracy.

Hence, the successful penetration and effective application of ESCO business models relies on minimizing the gap between actual and predicted building energy performance. An imperative step, towards this direction, is to understand building occupant behaviour and integrate it in dynamic building simulations addressing the optimization needs of different stages of the building lifecycle. Such a holistic optimization framework needs to enable: (1) Improved Predictions on the basis of more accurate and dynamically updated Building Energy Performance Simulation (BEPS) models; (2) Precise allocation and real-time assessment of detailed performance contributions of individual critical building components, (3) Real-time building performance optimization through control and maintenance, (4) Optimized retrofitting decision making on the basis of improved (LCA/ LCC-based) performance predictions.

Moreover the paradigm shift of the energy grid with the high penetration of renewable energy sources (RES) and complex energy systems that enable the interaction between buildings, requires such a holistic optimization framework [7] to be scalable in order to address and take advantage of complex interaction features in real-time energy performance and peak-load management optimization.

2. ADDRESSING CRITICAL NEEDS FOR MINIMIZING THE PERFORMANCE GAP

MOEEBIUS directly responds to the aforementioned needs with the introduction of a Holistic Energy Performance Optimization Framework that enhances current (passive and active building elements) modelling approaches. The MOEEBIUS solution comprises the configuration and integration of an innovative suite of end-user tools and applications enabling (i) improved Building Energy Performance Assessment on the basis of enhanced BEPS models (seamlessly addressing dynamic aspects of building operation, such as occupancy and weather conditions), that are iteratively and dynamically updated through feedback received from actual building measurements to allow for more accurate representation of the real-life complexities of the building, (ii) precise allocation of detailed performance contributions of critical building components, for directly assessing actual performance against predicted values and easily identifying performance deviations, their root causes and further optimization needs, (iii) real-time building performance optimization (during the operation and maintenance phase) including advanced simulation-based (human-centric) control and real-time self-diagnosis features, to resolve problems occurring due to user-behaviour, occupancy and climatic alterations and continuously tackle performance deviations that emerge throughout the building's life due to non-efficient controls, low performing systems or poor maintenance, (iv) optimized retrofitting decision making on the basis of improved and accurate LCA/ LCC-based (Life-Cycle Assessment/ Life-Cycle Cost) performance predictions, ensuring that the building performs as intended (regarding structural, environmental and energy performance, along with health, safety and comfort of occupants) and enabling optimized ROI along the building lifecycle and, (v) real-time peak-load management optimization at the district level. By upscaling the holistic optimization approach at the level of blocks of buildings and whole districts, MOEEBIUS addresses uncertainties imposed by the stochastic nature of intermittent RES and allows their efficient integration into the Smart Grid, through fine-grained control and exploitation of the aggregated capacity and flexibility of buildings and district heating systems in highly effective energy efficiency and demand response schemes.

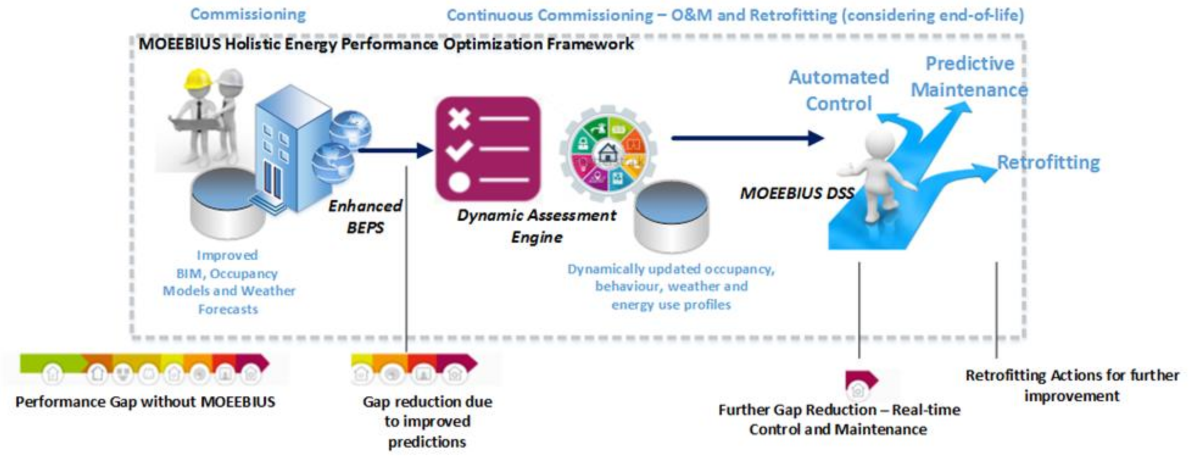

Figure 2. The MOEEBIUS Solution.

3. MOEEBIUS HOLISTIC ENERGY PERFORMANCE OPTIMIZATION FRAMEWORK

Energy performance optimization in buildings heavily relies on the deep and comprehensive understanding of real-life complexities imposed during actual operation. Such complexities span three interrelated groups of systems: physical systems (buildings, their equipment and their usage, along with districts and their systems), human systems (occupants and their behaviours) and the general surrounding environment (weather, its fluctuations and impact on the other systems). The inadequacy of current modelling approaches and simulation tools to effectively address these complexities is the root cause for significant prediction inaccuracies and performance deviations in actual buildings.

MOEEBIUS offers a Holistic Energy Performance Optimization Framework that treats occupants and their behaviour as the main catalyst of building sustainable operation. MOEEBIUS builds on top of dynamic modelling approaches, proven technological components and novel performance assessment and verification protocols towards enabling the alignment between predicted and actual building performance and the establishment of business friendly environments for ESCO market growth. This will be realized through the fusion of two (currently disjoint) worlds: (i) Building Information Modelling and (ii) Occupants’ Behaviour Modelling.

Through the combination of White-Box modelling techniques (at the level of BIM and District Modelling) and Black-Box modelling approaches (focusing on occupants’ behaviour) it delivers an innovative system that captures the real complexities of actual buildings and districts and allows for the correct understanding of user behaviour’s impact. Enhanced, accurate and dynamic behavioural (individual and/ or group) profiles complement improved static BIM models (with reduced simplifications and able to accommodate LCA-LCC parameters) to enable advanced and optimized predictions through, the appropriately configured, MOEEBIUS Building Performance Simulation Engine.

3.1. MOEEBIUS conceptual architecture

MOEEBIUS adopts the Internet of Things/Services principles to establish a Holistic Energy Performance Optimization Framework applied at building and district levels. Three innovative outcomes comprise the constituents of the MOEEBIUS Holistic Energy Performance Optimization Framework:

1. The Data Acquisition and Management Layer (MOEEBIUS-PIPE)
2. The Building & District level Dynamic Assessment Engines (MOEEBIUS-DAE)
3. The MOEEBIUS Integrated Decision Support System (MOEEBIUS-QUEST)

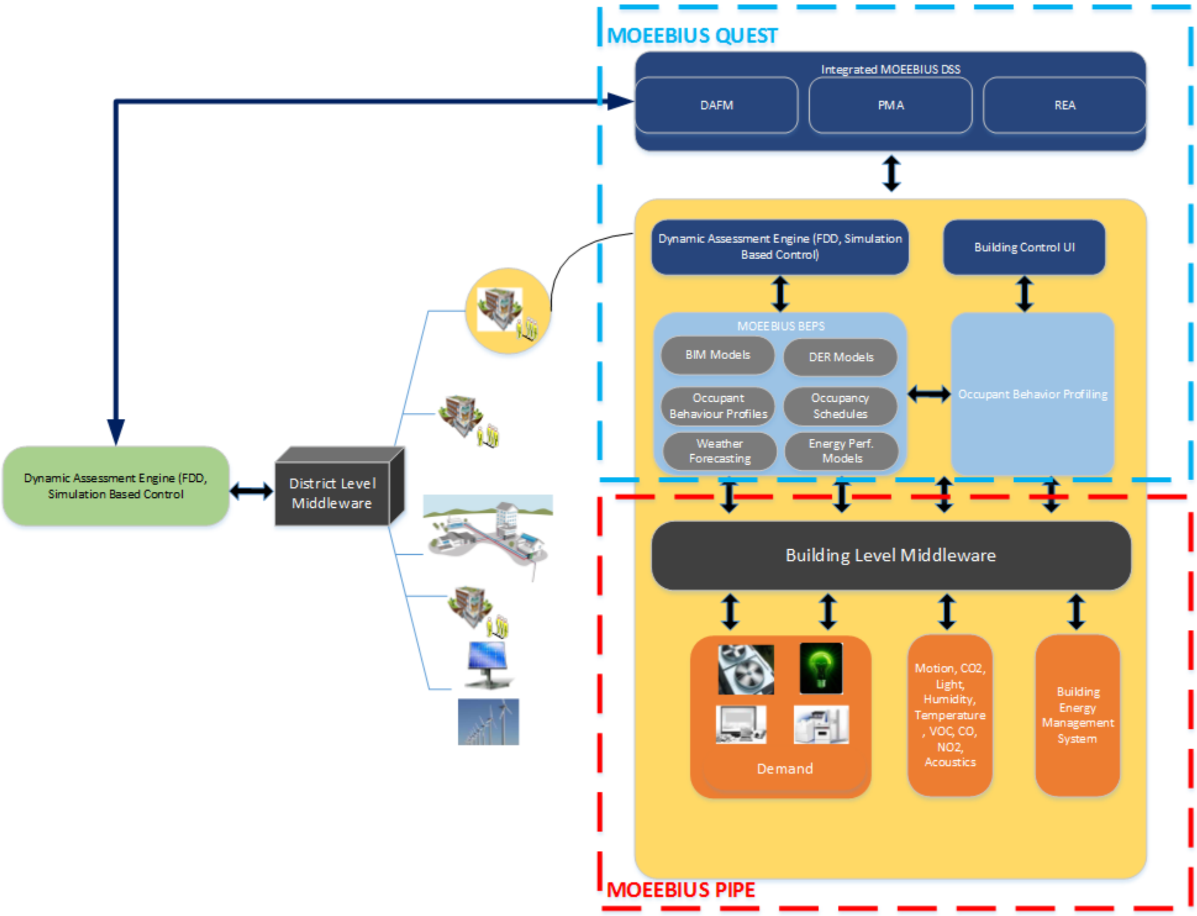

Figure 3. MOEEBIUS High-Level Conceptual Architecture.

3.2. MOEEBIUS-PIPE

The lowest level of the MOEEBIUS framework is the Data Acquisition and Management Layer (MOEEBIUS-PIPE) which is responsible for the collection of all necessary information, through Building Energy Management Systems (BEMS), District Heating Management Systems (DHMS), sensors deployed for monitoring ambient and hygienic conditions, energy meters and external sources (weather, pricing). Through open and semantically enhanced middleware infrastructures (applied both at the building and the district level). standardised multi-directional communication and control interfaces will be established between the individual building components and district-wide systems and the different MOEEBIUS modules and sub-systems. The semantic middleware establishes a seamless, transparent and homogeneous interface to all sensor/ actuator/ metering/ monitoring/ external components. Furthermore, it provides appropriately defined semantic virtual entities thus incorporating the necessary semantics for the efficient management of information streams from:

- Wireless Sensor/ Actuator Networks (WSAN) deployed in buildings to enable ambient conditions, health/wellbeing aspects, as well as energy sensing (where not covered by a BEMS) and enable the execution of control strategies (at the level of specific devices) upon specific controllable loads (heating, ventilation, air conditioning (HVAC) and lighting).
- Existing commercial BEMS and DHMS integrated with the middleware infrastructures to feed them with available and measured data in real-time, whilst enabling automated control strategies execution both for energy efficiency and peak-load management purposes.

3.3. MOEEBIUS-DAE

The MOEEBIUS performance optimization mechanisms will be based on an enhanced BEPS which comprises an enhanced version of the already available open-source and widely used EnergyPlus BEPS. The MOEEBIUS BEPS accommodates enhanced algorithmic concepts for bringing together improved BIM models, semantically enhanced Distributed Energy Resources (DER) models and dynamically updated occupant behaviour profiles, schedules and weather forecasts and utilizing them in building performance simulation iterations towards offering optimized performance predictions of high accuracy.

MOEEBIUS addresses occupant profiling and occupant’s behaviour as a fundamental factor for the optimisation of energy performance at building and district level, through the implementation of a framework that both addresses occupant preferences and is adaptive to the operational patterns of the monitoring area. The MOEEBIUS Occupant Profiling Mechanism (OPM) properly manage and train the enhanced integrated comfort models introduced in MOEEBIUS and utilize information streams from the WSAN. The profiling mechanism utilizes real-time energy data and ambient information in order to define dynamic consumer flexibility profiles and enable energy performance optimization through automated control strategies that balance energy performance with comfort and indoor quality requirements. The OPM is complemented with Ambient User Interfaces (AUI) for the building occupants that allow individual occupants to continuously interact with the building environment and provide the individual users with the necessary incentives towards more energy efficient choices. In addition, user preferences and choices are transparently fed back to the user profiling framework in order to provide the necessary alignment to the occupancy prediction module.

The MOEEBIUS Dynamic Assessment Engine (DAE) comprises a main innovation introduced in MOEEBIUS and is based on a Distributed Fuzzy Model Predictive Control (DFMPC) scheme. A method for control of large-scale multi-rate systems is adopted including fast and slow dynamics. These systems are multi-rate in the sense that either output measurements or input updates are not available at certain sampling times. Such issues can arise e.g. when the number of sensors is less than the number of variables to be controlled or when measurements of outputs cannot be completed simultaneously because of application limitations. The multi-rate nature gives rise to lack of information which causes uncertainty in the system's performance. To compensate the information loss due to multi-rate nature of the system a distributed Kalman filter [8] is applied to provide optimal estimation of the missing information. The distributed nature of the DAE enables implementation in a scalable way, setting an easily exportable structure at district level.

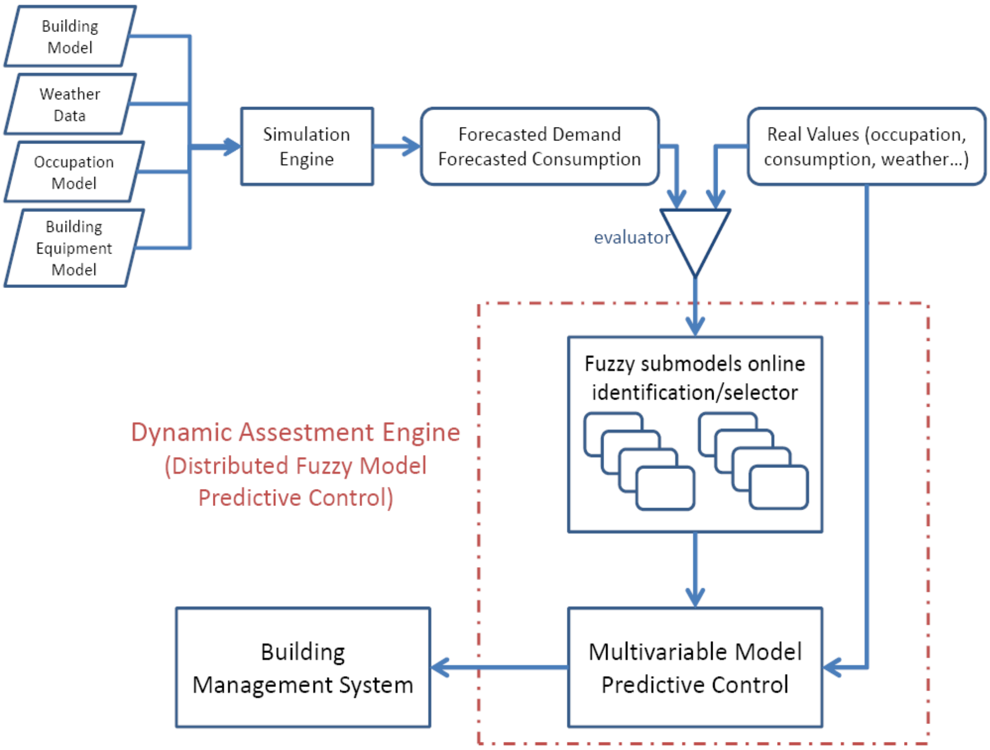

Figure 4. The MOEEBIUS Dynamic Assessment Engine – Conceptual Design.

3.4. MOEEBIUS-QUEST

Finally, the End-User Application Layer (MOEEBIUS-QUEST) accommodates the integrated MOEEBIUS Decision Support System (DSS) and respective applications for predictive/ sanitary maintenance, retrofitting strategies, evaluation and demand flexibility analysis, aggregation and forecasting, comprising the front-end for the end-users and enabling optimal decision making (not only in terms of near future actions for maintenance and retrofitting, but also in real-time, enabling fine-grained control for holistic energy performance optimization), through the integrated MOEEBIUS DSS.

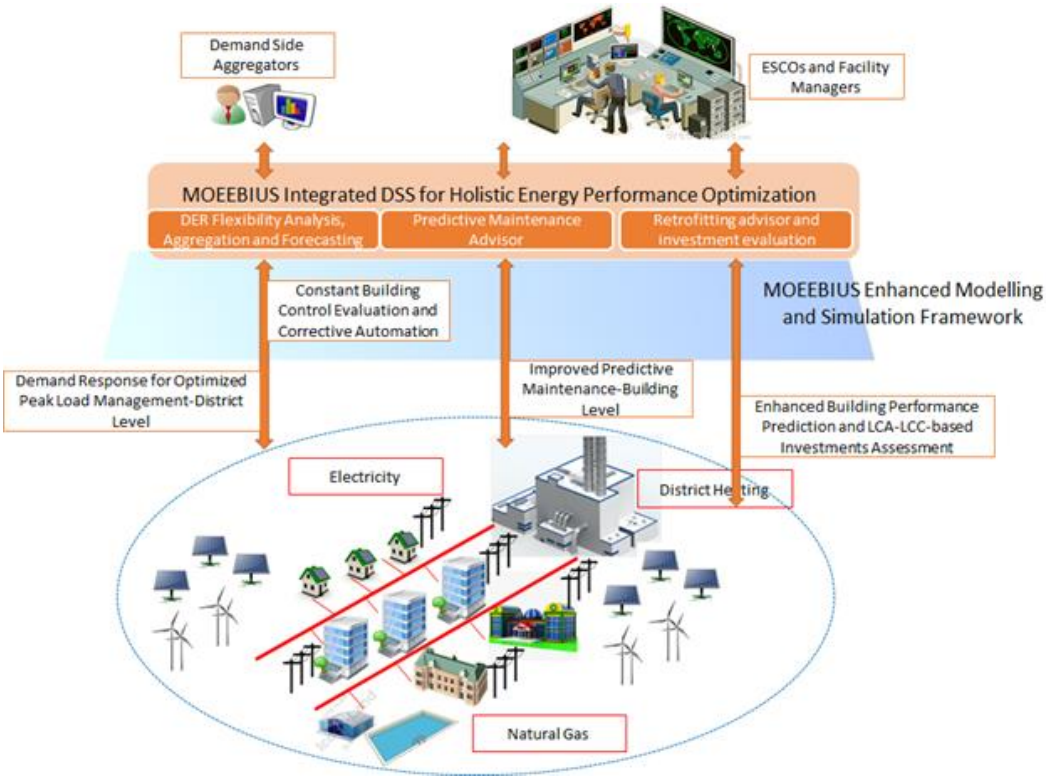

Figure 5. Conceptual Representation of dynamic real-time optimization features of MOEEBIUS.

4. CONCLUSIONS

By addressing occupants' behaviour, real HVAC performance and real weather conditions both at the BEPS (commissioning), as well as during the operation phase (real-time optimization on the basis of fine-grained control and automation), MOEEBIUS project aims to reduce the gap between energy prediction and real/ measured energy performance of buildings to values below 10%.

To further facilitate ESCO market growth and risk alleviation, the MOEEBIUS stepped optimization approach (improved prediction and fine-grained control) is further complemented with innovative maintenance and retrofitting decision-making tools that allow the evaluation of alternative maintenance/ retrofitting projects from an LCA-LCC point of view and further reduction of the performance gap through targeted actions upon poorly performing equipment and materials.

The holistic approach introduced in MOEEBIUS, spanning from BIM to user behaviour modelling and from retrofitting to human-centric Operation and Maintenance (O&M) improvements enable the establishment of a robust integrated technological framework that, ultimately, unleash the tremendous energy efficiency and demand response potential of the building sector. Subsequently, it enables the creation of attractive business opportunities for the MOEEBIUS end-users (ESCOs, Aggregators, Maintenance Companies and Facility Managers) in evolving and highly competitive energy services markets.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 680517.

REFERENCES

[1] A.C. Menezes, A. Cripps, D. Bouchlaghem, R. Buswell, "Predicted vs. actual energy performance", in roceedings of Third International Conference on Applied Energy, Perugia, Italy, May 16-18, 2011.

[2] J. Blanchard, S. Widder, E. Giever, M. Baechler, "Actual and Estimated Energy Savings Comparison for Deep Energy Retrofits in the Pacific Northwest", Pacific Northwest National Laboratory, N. p., Web. doi:10.2172/1057836 20122012, 2012

[3] CarbonBuzz platform, "Evidence". [Online]. Retrieved May 26, 2016, from http://www.carbonbuzz.org/evidencetab.jsp.

[4] M. Eguaras-Martínez, S. Krinidis, L. Makris, C. Martín-Gómez, P. Moschonas, I. Paliokas, N. Porfiriou, A. Tsakiris, T. Tsitsanis, M. Vidaurre, A. Zuazua, "Adapt4EE Evaluation Report", September, 2014. [Online]. Retrieved May 26, 2016, from http://www.adapt4ee.eu/adapt4ee/files/document/deliverables/Adapt4EE-Deliverable-D7.4.pdf

[5] M.S. de Wit, "Uncertainty in predictions of thermal comfort in buildings", doctoral thesis, Delft University of Technology, Delft, Netherlands, 2001.

[6] S. Kumar, "Top 5 Reasons Why ESCOs Have Failed to Realize the Full Potential of Energy Efficiency – Part II", December, 2014. [Online]. Retrieved May 26, 2016, from http://blog.schneider-electric.com/energy-management-energy-efficiency/2014/12/03/top-5-reasons-escos-failed-realize-full-potential-energy-efficiency-part-ii/.

[7] A. Romero, A. Egusquiza, J.L. Izkara, "Integrated decision support tool in energy retrofitting projects for sustainable urban districts", in Proceedings of World Sustainable Building 2014 Barcelona Conference, Barcelona, Spain, October 28-30, 2014.

[8] R.E. Kalman, "A new approach to linear filtering and prediction problems", *Transactions of the ASME – Journal of Basic Engineering*, No. 82 (Series D), pp. 35-45, 1960.